ENCLOSURE 2

WATTS BAR NUCLEAR PLANT UNIT 1
WCAP-16333-NP, DATED OCTOBER 2004
FRACTURE TOUGHNESS TESTING OF COMPACT TENSION SPECIMENS
FROM WATTS BAR UNIT 1 SURVEILLANCE CAPSULE X

Westinghouse Non-Proprietary Class 3

WCAP-16333-NP

October 2004

# Fracture Toughness Testing of Compact Tension Specimens from Watts Bar Unit 1 Surveillance Capsule X

Westinghouse

WCAP-16333-NP

(WCAP-16333-P has been reclassified from Proprietary Class 2 to Non-Proprietary Class 3.)

# Fracture Toughness Testing of Compact Tension Specimens from Watts Bar Unit 1 Surveillance Capsule X

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**October 2004**

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# 1 INTRODUCTION

This testing was conducted to supplement results from the Watts Bar Unit 1 Capsule X program. Capsule receipt and disassembly, along with the results of the standard Charpy and tensile testing have been previously described in reference [1]. Analysis of the capsule dosimetry indicated that the neutron fluence for this Capsule X was $1.71 \times 10^{19}$ n/cm$^2$ E >1 MeV. At the time of the original testing ½ T- Compact Tension (1/2 T-CT) specimens from the capsule were set aside for future testing.

Charpy impact test results from the intermediate shell forging indicate that this material has limited upper shelf toughness. Projections based on Regulatory Guide 1.99 Rev. 2 [2], indicate that the Charpy upper shelf energy will fall below 50 ft-lbs during the license period. Westinghouse has previously provided analysis demonstrating that the required margins against ductile fracture are maintained despite the relatively low Charpy upper shelf energy. [3] That analysis was based on a correlation between the Charpy upper shelf energy and the J-R fracture resistance curve behavior of pressure vessel steels. Adequate margin against fracture was demonstrated assuming a minimum Charpy upper shelf energy of 42 ft-lbs. Although the surveillance data indicate that the upper shelf energy continues to exceed this minimum, supplemental testing of the ½ T-CT surveillance specimens has been undertaken to determine the J-R fracture resistance curves for this material. The results should provide additional assurance that the intermediate shell forging meets the toughness requirements.

Results from testing of ½ T-CT specimens from Capsule W were reported by BWXT Services [4]. That report concluded that the vessel has margins of safety margins equivalent to the requirements of the ASME Code Appendix G. This report extends the Capsule W results by reporting the results of additional tests conducted on the ½ T-CT specimens from Capsule X.

# 2 PROOF-OF-PRINCIPLE TESTS

This study was undertaken to evaluate the feasibility of machining and testing 0.5T-CT fracture toughness specimens from Watts Bar Unit 1 surveillance Capsule X in the Westinghouse hotcell facilities. The testing program requires that the fracture toughness specimens be tested according ASTM Procedure E1820 [5] to produce J-R curves. The test method prefers displacement measurements on the load-line of the specimen. The test specimens contained in the Watts Bar surveillance program were not designed with notches that would allow the installation knife edges on the load line which would be required to accommodate a clip gage. The proposed testing program requires a modification to the specimen to enlarge the notch and provide integral knife-edges. This modification was employed in a previous testing program and has been approved by the NRC. Although the Westinghouse hotcells have extensive experience with J-integral tests on irradiated pressure vessel steels, the laboratory personnel were concerned about the feasibility of producing this specimen modification using existing equipment. This study was undertaken to evaluate the feasibility and provide a "Go / No-Go" recommendation before undertaking the modification and testing of the surveillance capsule specimens. This study concludes that the modification and testing of the fracture toughness specimens is feasible and provides a "Go" recommendation.

In the application developed at BWXT, the specimen modifications were produced by Electrical Discharge Machining (EDM). However, the preliminary evaluation at Westinghouse indicated that the existing hotcell EDM equipment would not be adequate for the precision machining required in this application. In addition, previous Westinghouse experience with EDM operations in the hotcell has indicated that the handling of the liquid wastes produced in this operation can be prohibitively expensive. As an alternative approach, Westinghouse proposed producing the same specimen modifications through more traditional mechanical milling operations. The primary concern was the quality of the knife edge produced by machining. In order to perform the unloading compliance tests, the clip gage must engage the knife edges cleanly.

A photograph of the machined specimen is included in Figure 2-1. The machined knife edges appear to be sharp and straight. The relief for the knife edge was machined in two steps. The shape of the knife edge did not match the notch in the standard Westinghouse clip gage. The clip gage was modified accordingly.

The machined specimen was tested at room temperature in the hotcell using the Instron JIC Fracture Toughness Program (Version 6.2.00) for Fast Track 2 Software. The unloadings were clean and the crack length measurements appeared to be steady and consistent. After approximately 0.035 inches of crack extension there was an apparent crack instability ("pop-in") event that caused the clip gage to slip out of the notch. This type of "pop-in" event should not normally occur in a J-R test, which is conducted on the upper shelf. The observation of a "pop-in" in this test is an indication that the upper shelf of the dummy material occurs slightly above room temperature. Investigation of this event led to the conclusion that the clip gage had been slightly misaligned during the modification of the notch. Adjustment of the clip gage led to a more secure seating in the knife edges. The partially cracked specimen was then reloaded in the test machine and additional unloadings were performed. Again the test results appeared acceptable.

At the end of the test, the specimen was heat tinted and then broken. The initial (0.515 inches) and final (0.702 inches) crack lengths were measured optically. These numbers correspond closely to the initial and final crack lengths indicated by the compliance unloading measurements (0.516 inches and 0.700 inches respectively). This close correspondence is a solid indication that the load-line displacement measurements were reliable.

The conclusion of this study is that the milling operation does produce suitable knife edges for the J-R test procedure. Therefore the recommendation is to proceed with the testing of the Watts Barr surveillance testing. Additional verification tests will be performed prior to the irradiated testing as part of the testing program.

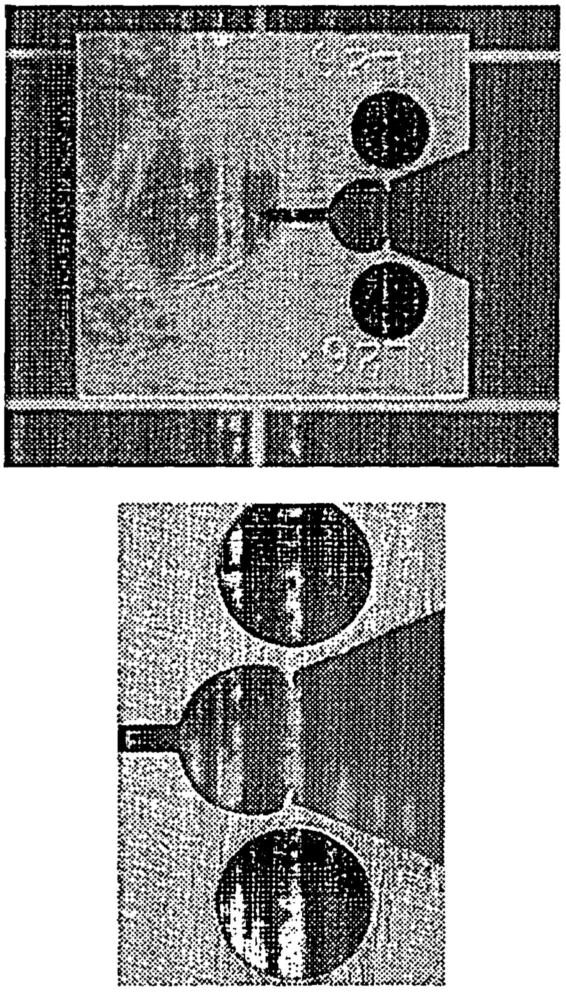


**Figure 2-1 Photograph of Modified ½ T-CT Specimen Including Blow-up of Cut Notch**

# 3 FRACTURE TOUGHNESS TESTS

## 3.1 SPECIMEN MACHINING AND PREPARATION

A total of four specimens were modified in the Westinghouse hot cell facility. The notch opening was machined to accommodate the load line displacement measurements. In addition, 12.5% sidegrooves were added to each side of the specimen. The sidegrooving removes curvature in the precrack near the edges and provides additional constraint during crack growth.

## 3.2 SPECIMEN TESTING

Procedures for testing of ½ T-CT specimens are outlined in Westinghouse Science and Technology Procedure MR 0003. These procedures are consistent with the requirements of ASTM Standard Test Method E1820. The tests are controlled using the Instron JIC Fracture Toughness Program (Version 6.2.00) for Fast Track 2 Software. This software records specimen load and crack mouth opening displacement along with the cross-head displacement during the test. A double cantilever beam clip gage was used to measure the crack mouth opening displacement (CMOD) on the load line. The hydraulic test machine was controlled using the CMOD measurement.

The Instron software records test data, controls the spacing of the specimen unloadings and provides online feedback on the approximate J-value and crack extension. The control program provides low load cycling prior to the test to set the clip gage in accordance to the test procedure. The program also requires unloading compliance measurements prior to the test which are both stable and consistent with the known crack length.

## 3.3 POST TEST MEASUREMENTS

At the conclusion of the test, the specimens were heat tinted at 550°F to mark the final crack front. The specimens were then reinserted into the test fixture and loaded to failure. The pre-crack and final crack lengths were determined using image analysis software and optical photographs of the fracture surface. Crack length determinations were based on the nine point weighted averaging technique required by ASTM Standard Test Method E1820.

## 3.4 POST TEST ANALYSIS

The analysis procedures embedded in the Instron testing software does not match the requirements of the current ASTM testing standard. Therefore all test results were analyzed using internally developed Excel spreadsheets. A special spreadsheet was developed to examine and analyze the compliance data. Each unloading curve was plotted and examined for irregularities in the data. Irregularities were most often observed at very low loads, where a portion of the test record tends to become non-linear. Irregularities were also observed in cases where crack growth appears approaches instability. Compliance determinations were limited to the linear portion of the curves. In all cases, the unloading compliance was confirmed by the reloading compliance. Crack lengths were determined using the equations provided in ASTM E1820. All measurements were corrected for rotation of the specimen.

The calculation of the J-integral requires knowledge of the load, the plastic area under the load-CMOD curve and the crack length. The intermediate values in the J calculation are provided in the test analysis records included in Appendix A.

ASTM E1820 provides a number of checks on the validity of the measured toughness. In order for the J determination to be valid, the pre-crack front and the final crack front must be straight across the specimen. The initial crack length, $a_{oq}$, is estimated from the J vs. crack extension curve by extrapolating the initial part of the curve back to J=0. The crack extension is determined by comparing the final crack length measurement to the initial value. The validity checks on crack extension require both an even crack front and accurate predictions of the crack lengths.

Validity limits are also placed on the maximum allowable J in the specimen based on the thickness and width of the uncracked portion of the specimen. As previously noted in the BWXT report [4], the J levels achieved in this relatively low toughness material never challenge the measurement capacity of the ½ T-CT specimens.

In the early portion of the J-integral test, the sharp starter notch will blunt as the load is increased. At the point of crack initiation, a new sharp crack will form and begin to grow. The J-integral toughness value at the initiation of ductile crack growth is usually characterized as $J_{IC}$. The $J_{IC}$ value is determined by extrapolating the crack growth portion of the J vs. crack extension curve back to the theoretical blunting line. The ASTM Standard provides both procedures for determining the intersection of the two curves and validity requirements on the quality of the determination.

There are a large number of validity requirements for the determination of $J_{IC}$ and it is sometimes difficult to achieve them all. Of the six specimens tested in the combined surveillance programs, only one (specimen WT11 from Capsule W) produced a valid $J_{IC}$ value. The remaining specimens were invalidated either by the crack front requirements or instabilities in the test records (the cause of these instabilities will be discussed in the following section). The invalid crack initiation values are reported as $J_Q$. Although the $J_Q$ measurements do not meet all of the validity requirements, they still contain valuable information about the toughness of the material. Comparison of the J-crack extension curves obtained in the two surveillance programs will give a fairly complete picture of the upper shelf fracture toughness of this material.

# 4 TEST RESULTS

## 4.1 OBSERVATION OF DUCTILE INSTABILITIES

All of the J-integral tests were conducted at 390°F, a temperature well into the upper shelf region for this material. At this temperature, the specimens would be expected to exhibit smooth ductile behavior. Although a full J vs. crack extension (J-R) curve was developed for the first specimen (WT13) from Capsule X, close inspection of the load vs. CMOD curve indicates that there were several small instabilities in the test record. These small "pop-in" events would not normally be expected in specimens tested on the upper shelf, where the fracture should be fully ductile. However, close inspection of the test records from Capsule W indicates that similar instabilities were encountered in the previous test program. The largest instability in the previous program occurred during the testing of Specimen WT9. The BWXT report attributed this behavior to a "low tearing resistance area" in the material, however it seems more likely that it was caused by a tearing instability as described below.

This culminated in the fracture of the second Capsule X specimen (WT14). This event was troubling because it seemed to indicate essentially no resistance to crack growth on the upper shelf. The fracture was extremely flat and there was little evidence of deformation. However SEM fractography (Figure 4-1) indicated that the fracture was entirely ductile. The large number of inclusions on the fracture surface and the relatively small rupture dimples are consistent with the low upper shelf of the material.

The fracture of SpecimenWT14 was caused by a ductile instability. This behavior is a more dramatic expression of the smaller instabilities observed in the previous specimens. Normally, a crack would not be expected to grow if the CMOD is held constant. Any growth in crack length at constant CMOD should cause a rapid drop in load, which would reduce the crack driving force. In this case it would be necessary to keep increasing the CMOD to keep the crack growing. However, no loading system is perfectly stiff and the hydraulic control system cannot keep pace with a rapidly growing crack. In this case, the test machine acts as a large spring in the system that maintains the load on the specimen as the crack grows. The factor used to measure the spring effect is the system compliance. The system compliance is simply defined as the change in total displacement per unit load with the specimen removed from the system. A ductile instability will occur when the compliance limits the load drop associated with crack value and the remaining load is sufficient to drive the crack through the specimen. Effectively instability occurs when the energy stored in the test machine "spring" is sufficient to fracture the specimen. Obviously an instability is more likely to occur in a specimen where the resistance to crack growth is low.

The occurrence of a ductile instability can be demonstrated by comparing the system compliance to the slope of the load vs. CMOD curve. If the compliance of the system matches the rate of load drop due to crack growth, the system becomes unstable and the specimen is torn apart ductilely. The system compliance may be estimated by examining the load vs. crosshead displacement curve. In the elastic portion of the test record, the slope of this curve is the sum of the system compliance and the specimen compliance. The sample compliance is routinely determined in these tests. Figure 4-2 compares the estimated system compliance to the load vs. CMOD curve for specimen WT13. By definition, the ductile instability must occur after maximum load, in the portion of the test where the load is dropping due to crack extension. Note that the slope of the compliance curve in Figure 4-2 has been reversed to facilitate the comparison. By inspection, it is evident that the system compliance closely matches the rate of load drop in the specimen. This close correspondence explains the instabilities observed in the specimen. Small variations in specimen behavior or the adjustment of the loading system may explain why Specimen WT13 developed a full crack extension curve and Specimen WT14 fractured.

Prior to the testing of the third specimen, the test frame was adjusted in an attempt to stiffen the system. The diameter of the pull rod was increased and all of the joints in the system were tightened. As indicated by the heavy dashed line in Figure 4-2, this produced a slight increase in the slope of the compliance curve (decrease in compliance). Because the instability in the specimen seemed to be marginal, it was hoped that this decrease in system compliance would reduce the instability. However when the third specimen (WT15) was tested, a large ductile instability occurred after a fairly short amount of ductile crack extension.

The practical implication of the ductile instability is that there is a lower limit on the toughness value (actually dJ/da) that can be determined in any test frame with a given specimen geometry. The fracture toughness of the Capsule X forging material is very near the lower limit for testing side-grooved ½ T-CT specimens in the Westinghouse Hot Cell test machine. Based on the fact that BWXT saw similar effects in their tests of the Capsule W specimens, it appears that the compliance of their system was similar to the Westinghouse system. The additional instability in the Capsule W specimens may be attributed to the increased irradiation level. It is important to note that the ductile instability is not an indication that the material has zero resistance to ductile tearing. It simply indicates that the resistance is below the measurement capability of the test system/specimen geometry combination.

## 4.2 TEST ANALYSIS

The load displacement records for the three Capsule X specimens tested are included in Figures 4-2 through 4-4. The initial portions of the three tests appear to be quite similar. Both specimens WT14 and WT15 exhibited unstable fracture shortly after achieving maximum load. Consistent with expectations, ductile instabilities only occurred after maximum load.

The J-R curves for the three Capsule X specimens are presented in Figures 4-5 through 4-7. The supporting calculations are provided in Appendix B. The R-curve for specimen WT13 was sufficient for the determination of a $J_Q$ value as indicated in Figure 4-5. The $J_Q$ value for this specimen was 563 in-lbs/in$^2$. The value could not be validated as $J_{IC}$ because it did not meet the validity requirements for crack extension. Although a full J-R curve was not defined for specimen WT15, there was sufficient crack extension to allow an estimate of the crack initiation point. A crack extension was fit to the shaded points in Figure 4-7 and used to estimate a crack initiation toughness of 573 in-lbs/in$^2$. Although the J value for specimen WT14 was 690 in-lbs/in$^2$ at the point of failure, the unloading compliance curve showed no evidence of crack extension.

The J-R curve for specimen WT13 was analyzed by fitting all of the points on the R-curve as indicated in Figure 4-8. The fitting parameters are summarized in Appendix A. The J value at a crack extension of 0.1 inch crack extension was determined to be 812 in-lbs/in$^2$ based on this fit. The fit can also be used to determine the dJ/da value as a function of crack extension as illustrated in Figure 4-8. At 0.1 inch crack extension, the dJ/da value for specimen WT13 was 1346 in-lbs/in$^2$/in. Although only a limited number of crack extension data were available for specimen WT15, the data can be extrapolated to a J value of 943 in-lbs/in$^2$ and a dJ/da value of 2152 in-lbs/in$^2$/in at 0.1 inch.

The results of the J-integral fracture toughness tests on the Capsule X specimens are summarized in Table 4-1.

| Table 4-1 Summary of Fracture Toughness Data | | | | |
|---|---|---|---|---|
| Specimen | Crack Initiation $J_Q$ in-lbs/in$^2$ | J at Instability in-lbs/in$^2$ | J at $\Delta a$=0.1 inch in-lbs/in$^2$ | dJ/da at $\Delta a$=0.1 inch in-lbs/in$^2$/in |
| WT13 | 563 | – | 812 | 1346 |
| WT14 | – | 693 | – | – |
| WT15 | 573* | 664 | 943* | 2152* |
| * Estimated value | | | | |

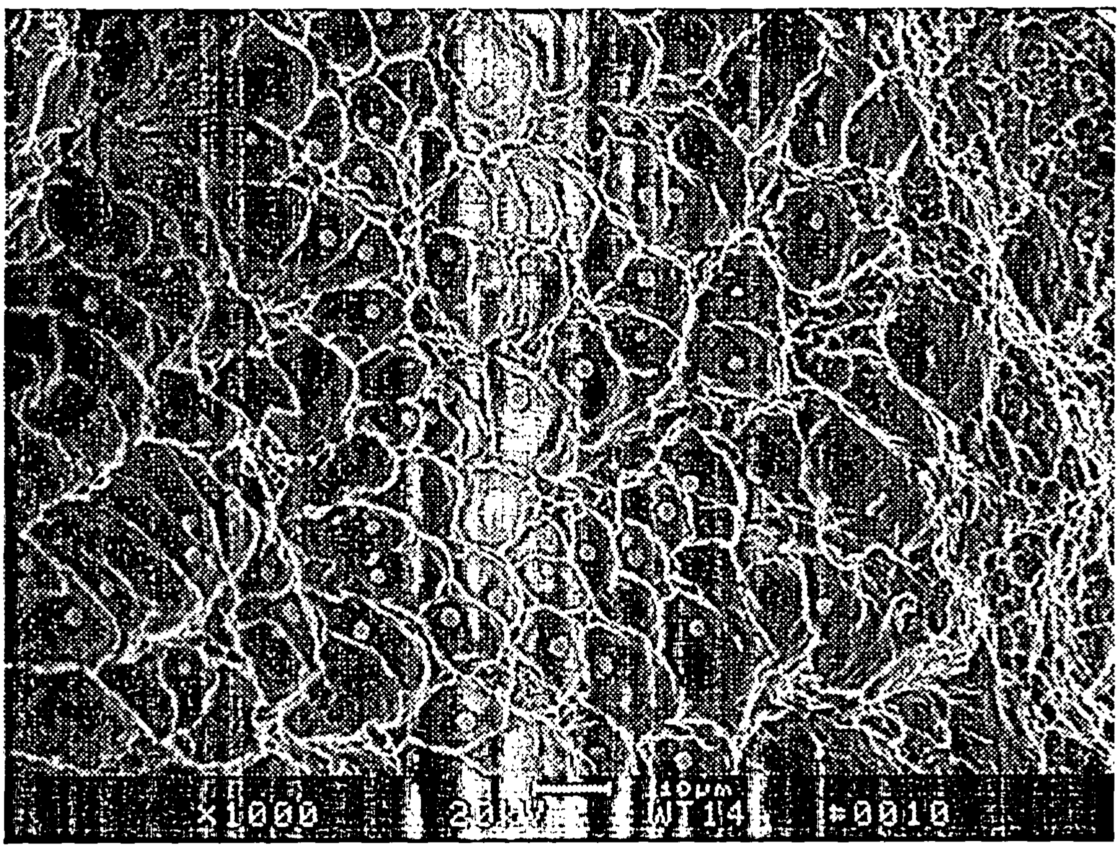



**Figure 4-1 SEM Fractograph of Ductile Failure in Specimen WT14. This area is typical of the entire surface.**

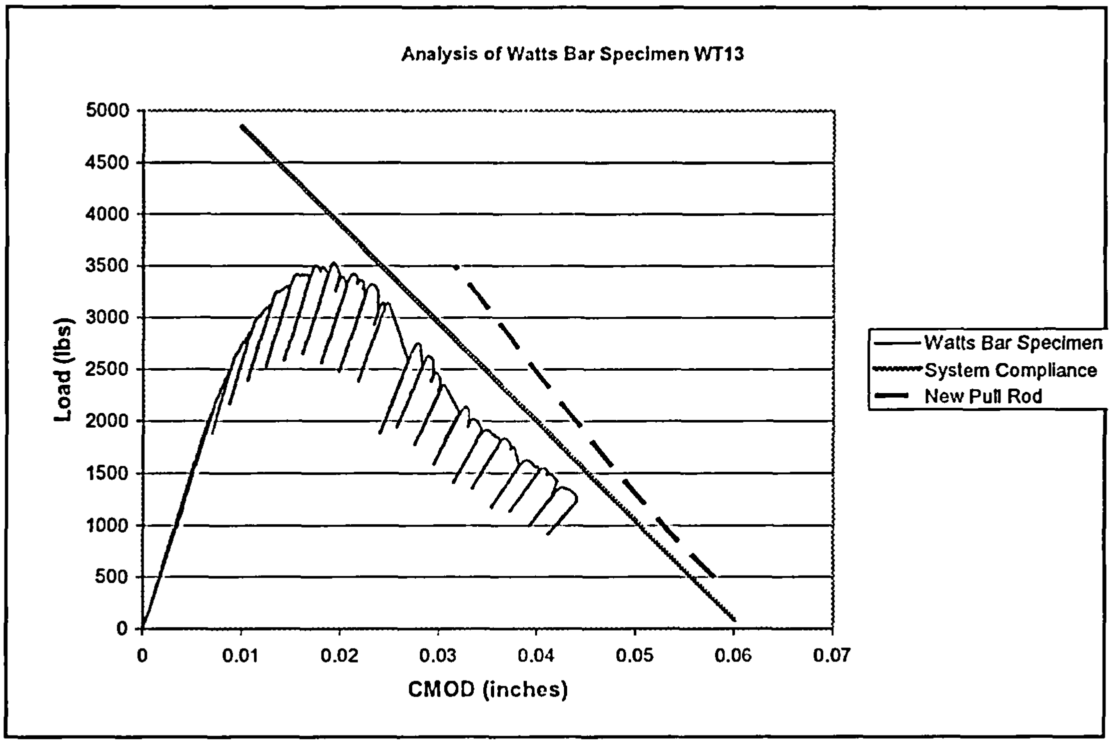



Figure 4-2 Comparison of System Compliance to Test Record for Specimen WT13

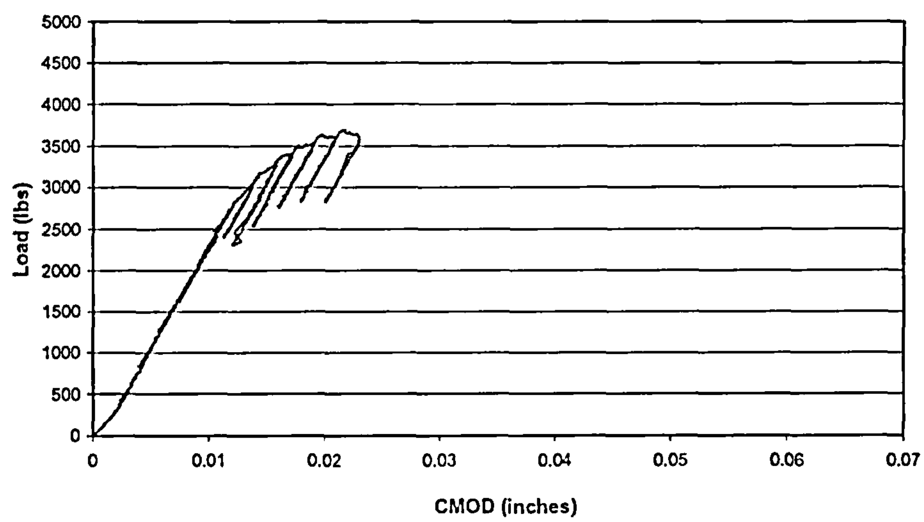



Figure 4-3 Test Record for Specimen WT14

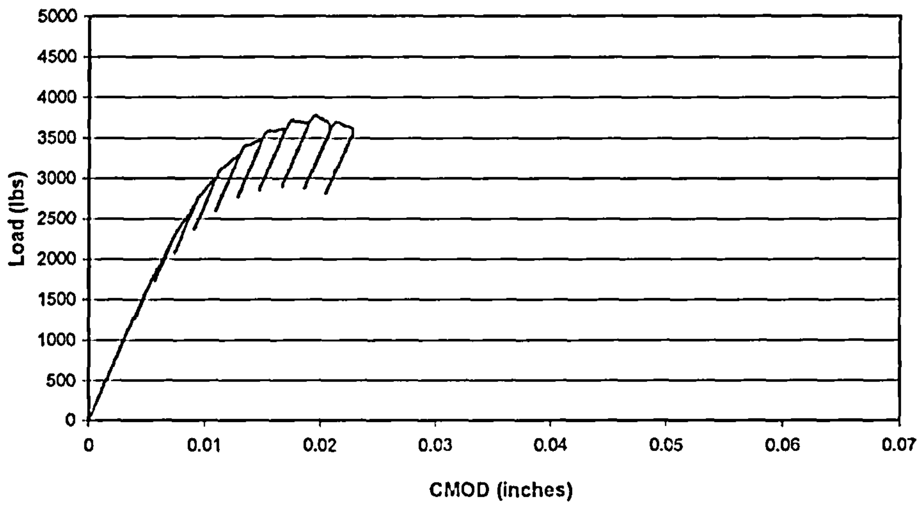



Figure 4-4, Test Record for Specimen WT15

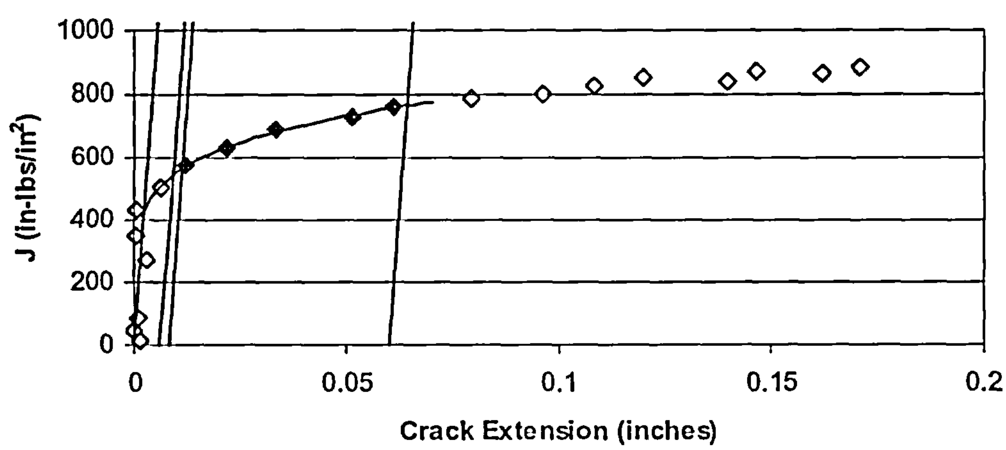



Figure 4-5 $J_{IC}$ Analysis of Specimen WT13

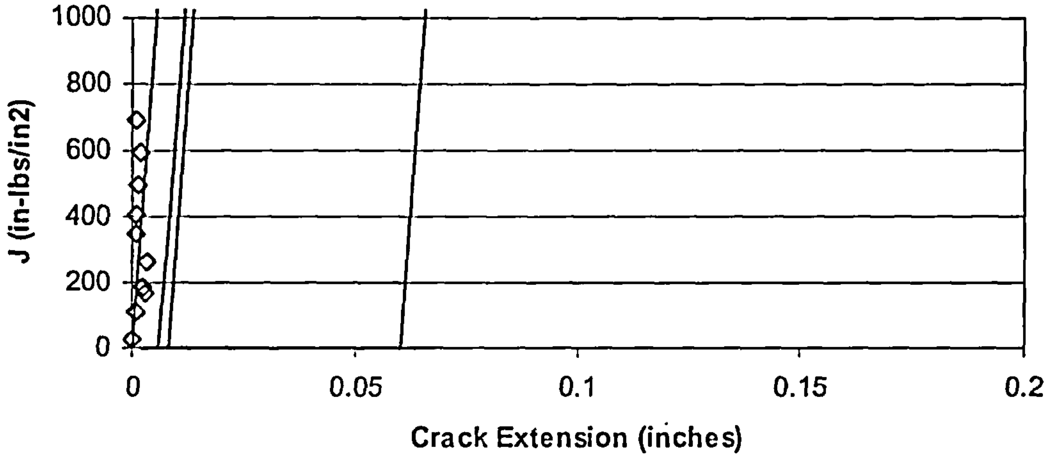



Figure 4-6 Partial J–R Curve for Specimen WT14

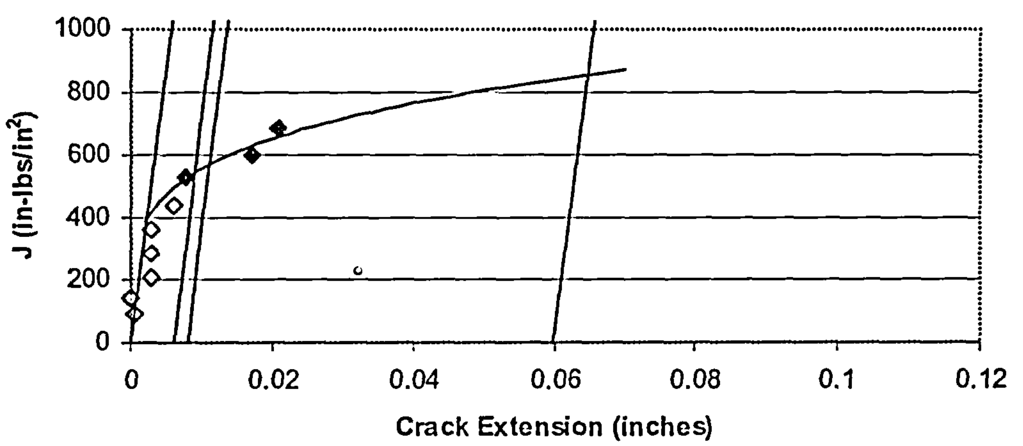



Figure 4-7 Partial J-R curve for specimen WT15

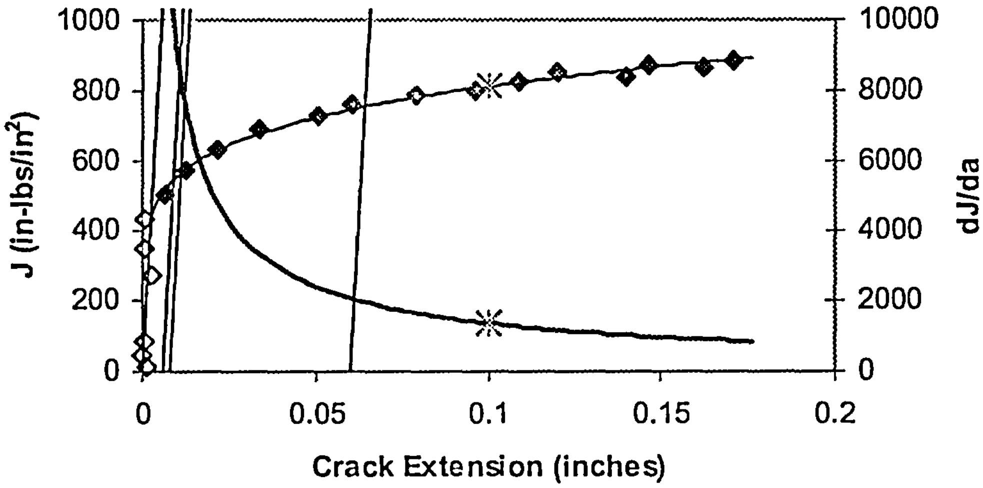



Figure 4-8 Analysis of J-R Curve for Specimen WT13

# 5 DISCUSSION

The objective of this study was to demonstrate that the plant specific J-R curves from the Capsule X specimens meet the requirements for resistance to ductile tearing as defined by ASME Section XI, Appendix X. This study is an extension of the previously reported Capsule W evaluation. The minimum fracture toughness for the Watts Bar Unit 1 vessel were originally established by Westinghouse and summarized in the BWXT report. Those fracture toughness requirements are summarized in Table 5-1.

**Table 5-1 Fracture Toughness Requirements for Watts Bar Unit 1 Reactor Vessel**

| Loading Condition | Applied J at $\Delta a$=0.1 inch in-lbs/in$^2$ | Applied dJ/da in-lbs/in$^2$/in |
|---|---|---|
| Level A and B | 590 | 345 |
| Level C | 314 | 320 |
| Level D | – | 380 |

The Capsule X J-R curves are compared to the previously reported Capsule W curves in Figure 5-1. The J-R curve for specimen WT13 provides a lower bound for all of the fracture toughness tests on the irradiated intermediate forging material. Based on this result, it appears that increasing the neutron fluence from $1.23 \times 10^{19}$ to $1.71 \times 10^{19}$ n/cm2 (E> 1MeV) produced a small decrease in fracture toughness. Over this same range of fluences, the Charpy upper shelf energy of the intermediate shell forging material was essentially unchanged. Although full R-curves were not developed for Specimens WT14 and WT15, the partial curves verify the toughness observed in WT13.

The observed J-R curves exceed the minimum fracture toughness requirements outlined in Table 5-1. Although two of the specimens failed prior to reaching 0.1 inches of crack growth, they both exhibited well in excess of the required minimum at failure. The J fracture toughness value of 813 in-lbs/in$^2$ observed in specimen WT13 at 0.1 inch crack extension appears to be representative of this material. Although this material exhibits a relatively low resistance to ductile tearing, the dJ/da value 1346 at 0.1 inch crack extension for specimen WT13 is still well in excess of the minimum required value.

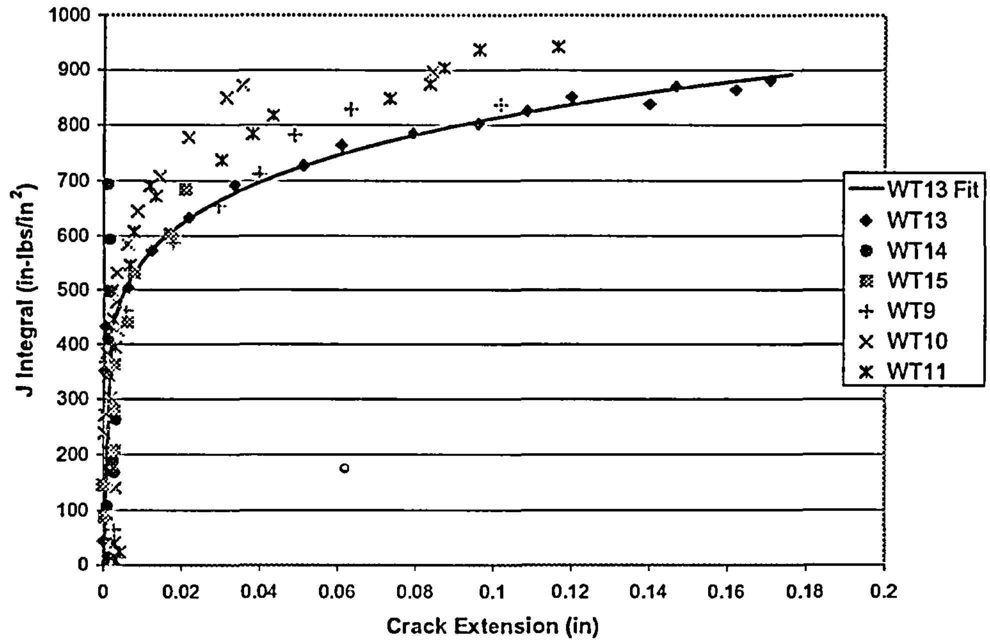



**Figure 5-1 Comparison of J-R Curves for Watts Bar Unit 1 Surveillance Specimens**

# 6 REFERENCES


1. WCAP-16245-NP, *Analysis of Capsule X from Tennessee Valley Authority, Watts Bar Unit 1 Reactor Vessel Radiation Surveillance Program*, T.J. Laubham, J. Conermann and C. Doumont, Westinghouse Electric, April 2004.

2. Regulatory Guide 1.99 Revision 2, *Radiation Embrittlement of Reactor Vessel Materials*, U.S. Nuclear Regulatory Commission, May 1988.

3. *Watts Bar Unit 1 Low Upper Shelf Evaluation*, TVA Contract 92NNP-79283A, Westinghouse Electric, August 1993.

4. *Analysis of J-R Curves Generated from Capsule W 1/2T Compact Tension Specimens of the Tennessee Valley Authority Watts Bar Unit 1 Reactor Vessel Material Surveillance Program*, W.A. Pavinich, BWXT Services, Lynchburg VA, September 2001.

5. ASTM E1820-01, *Standard Test Method for Measurement of Fracture Toughness*.

# APPENDIX A
# TEST RECORDS AND ANALYSIS FOR SPECIMENS WT13, WT14 AND WT15

## J-Integral Test Parameters

| | | |
|---|---|---|
| Operator's Name: | G.Evans | |
| Job Number: | WATTS BARS | |
| Specimen ID: | WT-13 | |
| Material: | RPV Steel | |
| Test Temperature: | 390 | F |
| Test Date: | 4/5/04 | |
| Test Param File Name: | WATTS BAR WT-13 390 F-1 | |
| Young's Modulus: | 27500000 | psi |
| Yield Stress: | 78000 | psi |
| Tensile Strength: | 99000 | psi |
| Poisson's Ratio: | 0.3 | |
| Specimen Type | CT | |
| Width: | 1 | in |
| B gross: | 0.5 | in |
| B net: | 0.375 | in |
| Load Point Half Span: | 0.275 | in |
| COD HALF Span: | 0.0775 | in |
| Ramp Rate for Load/Unload: | 0.000167 | in/sec |
| LPD Start Point for Load/Unload: | 0.003 | in |
| LPD Increment for Load/Unload : | 0.002 | in |
| Hold Duration at Peak: | 6 | sec |

# Specimen WT13 Crack Length Calculations

| Unload Number | Load (lbs) | Displacement (inches) | Unloading Compliance (inch/lb) | Radius of Rotation | Theta (degrees) | Corrected Compliance (in/lb) | Normalized Compliance ($B_eEC$) | u | Crack Length (inches) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 903 | 0.003001 | 3.2215E-06 | 0.76623833 | 0.112212 | 3.22442E-06 | 41.56478482 | 0.134281 | 0.523099 |
| 2 | 1527 | 0.004987 | 3.1957E-06 | 0.76154939 | 0.187632 | 3.2006E-06 | 41.2576767 | 0.134713 | 0.521657 |
| 3 | 2071 | 0.006892 | 3.2103E-06 | 0.76082862 | 0.259569 | 3.21712E-06 | 41.47070172 | 0.134413 | 0.522659 |
| 4 | 2485 | 0.008812 | 3.1649E-06 | 0.7613293 | 0.331684 | 3.17351E-06 | 40.90854783 | 0.135209 | 0.520002 |
| 5 | 2847 | 0.010791 | 3.151E-06 | 0.76000097 | 0.406913 | 3.16156E-06 | 40.7545002 | 0.135429 | 0.519266 |
| 6 | 3111 | 0.012842 | 3.2369E-06 | 0.75963296 | 0.484523 | 3.24993E-06 | 41.89356974 | 0.133824 | 0.524627 |
| 7 | 3293 | 0.014754 | 3.1926E-06 | 0.76231363 | 0.55474 | 3.20724E-06 | 41.34329805 | 0.134592 | 0.52206 |
| 8 | 3402 | 0.016723 | 3.1932E-06 | 0.76103025 | 0.629879 | 3.20993E-06 | 41.37797427 | 0.134543 | 0.522224 |
| 9 | 3424 | 0.018619 | 3.2872E-06 | 0.76111175 | 0.701265 | 3.30637E-06 | 42.62120285 | 0.132829 | 0.527957 |
| 10 | 3339 | 0.020453 | 3.3893E-06 | 0.76397834 | 0.767497 | 3.41095E-06 | 43.96926706 | 0.131046 | 0.533938 |
| 11 | 3277 | 0.02234 | 3.5624E-06 | 0.76696923 | 0.83509 | 3.58718E-06 | 46.24102905 | 0.128204 | 0.543507 |
| 12 | 3131 | 0.024361 | 3.7906E-06 | 0.77175353 | 0.905048 | 3.8191E-06 | 49.2305387 | 0.124744 | 0.555214 |
| 13 | 2426 | 0.026303 | 4.1725E-06 | 0.77760691 | 0.969896 | 4.20598E-06 | 54.21767582 | 0.119571 | 0.572815 |
| 14 | 2674 | 0.028154 | 4.4074E-06 | 0.78640736 | 1.026578 | 4.44443E-06 | 57.29141894 | 0.116698 | 0.582633 |
| 15 | 2333 | 0.030108 | 4.896E-06 | 0.79131646 | 1.091078 | 4.93962E-06 | 63.67479418 | 0.111363 | 0.600943 |
| 16 | 2076 | 0.032077 | 5.4134E-06 | 0.80047166 | 1.149189 | 5.46376E-06 | 70.43131942 | 0.10647 | 0.617806 |
| 17 | 1845 | 0.034003 | 5.847E-06 | 0.80890293 | 1.205545 | 5.90365E-06 | 76.10176405 | 0.102842 | 0.630342 |
| 18 | 1835 | 0.036134 | 6.2824E-06 | 0.81517085 | 1.271317 | 6.34625E-06 | 81.80707687 | 0.099555 | 0.641723 |
| 19 | 1555 | 0.038034 | 7.1684E-06 | 0.82086167 | 1.328952 | 7.24429E-06 | 93.38341464 | 0.093778 | 0.661762 |
| 20 | 1554 | 0.040082 | 7.5024E-06 | 0.83088103 | 1.383677 | 7.58434E-06 | 97.76684637 | 0.091847 | 0.668469 |
| 21 | 1332 | 0.041957 | 8.3534E-06 | 0.83423463 | 1.442657 | 8.4484E-06 | 108.9052108 | 0.087445 | 0.68377 |
| 22 | 1263 | 0.043973 | 8.8941E-06 | 0.84188523 | 1.498299 | 8.99857E-06 | 115.9971756 | 0.08496 | 0.692414 |

## Specimen WT13
## Physical Crack Lengths

| | Precrack | | | Precrack |
|---|---|---|---|---|
| Side 1 | 0.527 | | Side 1 | 0.7644 |
| 1/8 point | 0.5225 | | 1/8 point | 0.7531 |
| 1/4 point | 0.5248 | | 1/4 point | 0.7348 |
| 3/8 point | 0.527 | | 3/8 point | 0.7462 |
| 1/2 point | 0.527 | | 1/2 point | 0.7325 |
| 5/8 point | 0.5225 | | 5/8 point | 0.7188 |
| 3/4 point | 0.5202 | | 3/4 point | 0.6869 |
| 7/8 point | 0.5156 | | 7/8 point | 0.68 |
| Side 2 | 0.5111 | | Side 2 | 0.7074 |
| | | | | |
| length | 0.522 | | length | 0.724 |

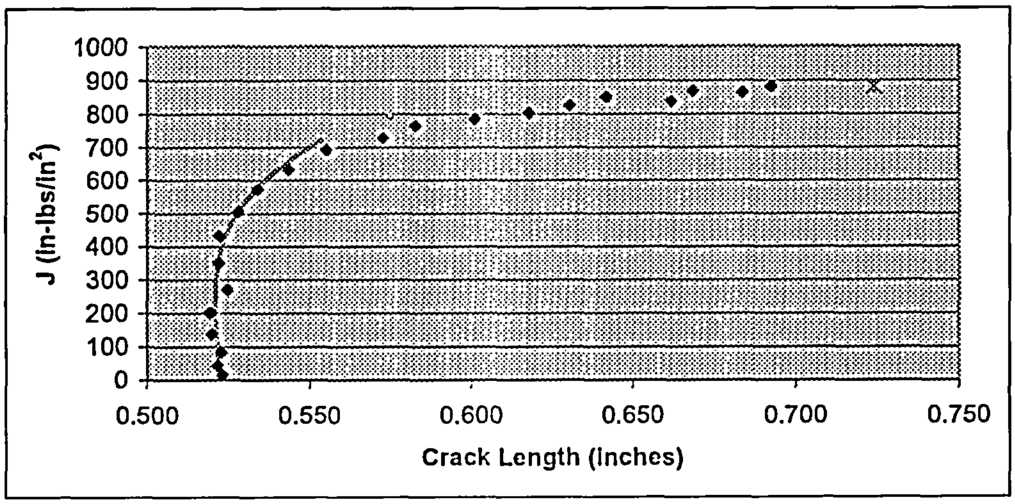
Validity Requirements

| | | | |
|---|---|---|---|
| 7.4.2 | Fatigue Precrack = | 0.084 > .050 | Valid |
| | Initial a/W = | 0.522 | Valid |
| 7.4.5 | Precracking Conducted Prior to Irradiation | | Valid |
| 9.1.4.1 | Original Crack Size | | |
| | Min. Variance = | 2.15% | Valid |
| | Max. Variance = | 0.89% | |
| 9.1.4.2 | Final Crack Size | | |
| | Min. Variance = | 6.02% | Invalid |
| | Max. Variance = | 5.65% | Invalid |
| 9.1.5.1 | Crack Extension | | |
| | Average = | 0.201 inches | |
| | Min= | 78% | Valid |
| 9.1.5.2 | Crack Extension Prediction | | |
| | Measured = | 0.201 | |
| | Predicted = | 0.170738 | |
| | Prediction Error = | 0.030456 | |
| | $0.2\ b_o$ = | 0.095665 | |
| | Crack Extension > $0.2\ b_o$ | | |
| | Prediction Error Should be less than: | | |
| | $0.03\ b_o$ = | 0.0111 | Invalid |

## Specimen WT13 Determination of J-Integral

| Unload Number | Load (lbs) | Displacement (inches) | Corrected Compliance (in/lb) | Crack Length (inches) | a/W | Plastic Displacement (inches) | Plastic Area (in-lbs) | f(a/W) | K (ksi-in$^{1/2}$) | Jelastic (in-lbs/in$^2$) | eta | gamma | Jplastic (in-lbs/in$^2$) | Jtotal (in-lbs/in$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 903 | 0.00300 | 3.2244E-06 | 0.5231 | 0.5231 | 0.00009 | 0.040734 | 10.389 | 21.66 | 15.52 | 2.248942 | 1.362445 | 0.00 | 15.52 |
| 2 | 1527 | 0.00499 | 3.2006E-06 | 0.5217 | 0.5217 | 0.00010 | 0.050915 | 10.341 | 36.47 | 44.02 | 2.249695 | 1.363541 | 0.13 | 44.15 |
| 3 | 2071 | 0.00689 | 3.2171E-06 | 0.5227 | 0.5227 | 0.00023 | 0.28823 | 10.374 | 49.61 | 81.44 | 2.249172 | 1.362779 | 3.10 | 84.54 |
| 4 | 2485 | 0.00881 | 3.1735E-06 | 0.5200 | 0.5200 | 0.00093 | 1.873873 | 10.286 | 59.02 | 115.28 | 2.250559 | 1.364799 | 23.09 | 138.36 |
| 5 | 2847 | 0.01079 | 3.1616E-06 | 0.5193 | 0.5193 | 0.00179 | 4.176827 | 10.262 | 67.46 | 150.61 | 2.250943 | 1.365358 | 51.95 | 202.56 |
| 6 | 3111 | 0.01284 | 3.2499E-06 | 0.5246 | 0.5246 | 0.00273 | 6.975248 | 10.441 | 75.02 | 186.25 | 2.248145 | 1.361283 | 85.94 | 272.18 |
| 7 | 3293 | 0.01475 | 3.2072E-06 | 0.5221 | 0.5221 | 0.00419 | 11.65457 | 10.354 | 78.75 | 205.23 | 2.249484 | 1.363234 | 145.69 | 350.92 |
| 8 | 3402 | 0.01672 | 3.2099E-06 | 0.5222 | 0.5222 | 0.00580 | 17.04824 | 10.360 | 81.40 | 219.24 | 2.249399 | 1.36311 | 213.31 | 432.55 |
| 9 | 3424 | 0.01862 | 3.3064E-06 | 0.5280 | 0.5280 | 0.00730 | 22.1497 | 10.554 | 83.47 | 230.53 | 2.246407 | 1.358753 | 273.53 | 504.06 |
| 10 | 3339 | 0.02045 | 3.4109E-06 | 0.5339 | 0.5339 | 0.00906 | 28.12114 | 10.764 | 83.01 | 228.04 | 2.243284 | 1.354207 | 344.18 | 572.21 |
| 11 | 3277 | 0.02234 | 3.5872E-06 | 0.5435 | 0.5435 | 0.01058 | 33.15394 | 11.115 | 84.12 | 234.18 | 2.238289 | 1.346935 | 398.49 | 632.67 |
| 12 | 3131 | 0.02436 | 3.8191E-06 | 0.5552 | 0.5552 | 0.01241 | 38.9897 | 11.571 | 83.66 | 231.59 | 2.232178 | 1.338037 | 459.90 | 691.48 |
| 13 | 2426 | 0.02630 | 4.2060E-06 | 0.5728 | 0.5728 | 0.01610 | 49.25592 | 12.321 | 69.02 | 157.64 | 2.222991 | 1.324661 | 569.71 | 727.34 |
| 14 | 2674 | 0.02815 | 4.4444E-06 | 0.5826 | 0.5826 | 0.01627 | 49.69237 | 12.776 | 78.88 | 205.89 | 2.217866 | 1.317199 | 557.96 | 763.85 |
| 15 | 2333 | 0.03011 | 4.9396E-06 | 0.6009 | 0.6009 | 0.01858 | 55.47532 | 13.705 | 73.85 | 180.48 | 2.208308 | 1.303283 | 604.76 | 785.25 |
| 16 | 2076 | 0.03208 | 5.4638E-06 | 0.6178 | 0.6178 | 0.02073 | 60.21916 | 14.667 | 70.32 | 163.65 | 2.199505 | 1.290468 | 638.88 | 802.53 |
| 17 | 1845 | 0.03400 | 5.9037E-06 | 0.6303 | 0.6303 | 0.02311 | 64.87612 | 15.460 | 65.88 | 143.64 | 2.192962 | 1.28094 | 681.58 | 825.22 |
| 18 | 1835 | 0.03613 | 6.3462E-06 | 0.6417 | 0.6417 | 0.02449 | 67.42097 | 16.244 | 68.82 | 156.72 | 2.18702 | 1.27229 | 693.69 | 850.41 |
| 19 | 1555 | 0.03803 | 7.2443E-06 | 0.6618 | 0.6618 | 0.02677 | 71.28484 | 17.798 | 63.90 | 135.11 | 2.17656 | 1.257061 | 703.00 | 838.12 |
| 20 | 1554 | 0.04008 | 7.5843E-06 | 0.6685 | 0.6685 | 0.02829 | 73.65035 | 18.374 | 65.96 | 143.95 | 2.173059 | 1.251963 | 725.49 | 869.44 |
| 21 | 1332 | 0.04196 | 8.4484E-06 | 0.6838 | 0.6838 | 0.03070 | 77.12347 | 19.812 | 60.97 | 123.00 | 2.165072 | 1.240334 | 741.33 | 864.32 |
| 22 | 1263 | 0.04397 | 8.9986E-06 | 0.6924 | 0.6924 | 0.03261 | 79.60443 | 20.708 | 60.38 | 120.65 | 2.16056 | 1.233765 | 760.43 | 881.08 |

## Specimen WT13 $a_{oq}$ Calculations




aoq = 0.5217

Measured Final= 0.724

| Unload Number | Load (lbs) | Displacement (inches) | Jtotal (in-lbs/in²) | Crack Length (inches) | a-J/2σy (inches) | $J^2$ | $J^3$ |
|---|---|---|---|---|---|---|---|
| 1 | 903 | 0.00300 | 15.52 | 0.5231 | 0.5230 | 240.95 | 3740 |
| 2 | 1527 | 0.00499 | 44.15 | 0.5217 | 0.5214 | 1949.33 | 86065 |
| 3 | 2071 | 0.00689 | 84.54 | 0.5227 | 0.5222 | 7146.85 | 604188 |
| 4 | 2485 | 0.00881 | 138.36 | 0.5200 | 0.5192 | 19144.86 | 2648978 |
| 5 | 2847 | 0.01079 | 202.56 | 0.5193 | 0.5181 | 41029.37 | 8310789 |
| 6 | 3111 | 0.01284 | 272.18 | 0.5246 | 0.5231 | 74084.14 | 20164519 |
| 7 | 3293 | 0.01475 | 350.92 | 0.5221 | 0.5201 | 123146.87 | 43215053 |
| 8 | 3402 | 0.01672 | 432.55 | 0.5222 | 0.5198 | 187098.74 | 80929393 |
| 9 | 3424 | 0.01862 | 504.06 | 0.5280 | 0.5251 | 254080.03 | 128072474 |
| 10 | 3339 | 0.02045 | 572.21 | 0.5339 | 0.5307 | 327428.22 | 187358824 |
| 11 | 3277 | 0.02234 | 632.67 | 0.5435 | 0.5399 | 400270.57 | 253238942 |
| 12 | 3131 | 0.02436 | 691.48 | 0.5552 | 0.5513 | 478149.75 | 330632773 |
| 13 | 2426 | 0.02630 | 727.34 | 0.5728 | 0.5687 | 529025.89 | 384782564 |
| 14 | 2674 | 0.02815 | 763.85 | 0.5826 | 0.5783 | 583467.28 | 445681659 |
| 15 | 2333 | 0.03011 | 785.25 | 0.6009 | 0.5965 | 616615.03 | 484195963 |
| 16 | 2076 | 0.03208 | 802.53 | 0.6178 | 0.6133 | 644054.79 | 516873445 |
| 17 | 1845 | 0.03400 | 825.22 | 0.6303 | 0.6257 | 680985.74 | 561962103 |
| 18 | 1835 | 0.03613 | 850.41 | 0.6417 | 0.6369 | 723201.56 | 615019711 |
| 19 | 1555 | 0.03803 | 838.12 | 0.6618 | 0.6570 | 702441.70 | 588729000 |
| 20 | 1554 | 0.04008 | 869.44 | 0.6685 | 0.6636 | 755918.70 | 657222821 |
| 21 | 1332 | 0.04196 | 864.32 | 0.6838 | 0.6789 | 747050.90 | 645691822 |
| 22 | 1263 | 0.04397 | 881.08 | 0.6924 | 0.6874 | 776300.52 | 683982226 |

Validity Requirements

9.8.2.1 Error in aoq prediction less than 0.01W

aoq = 0.5217

Measured = 0.5223 Valid

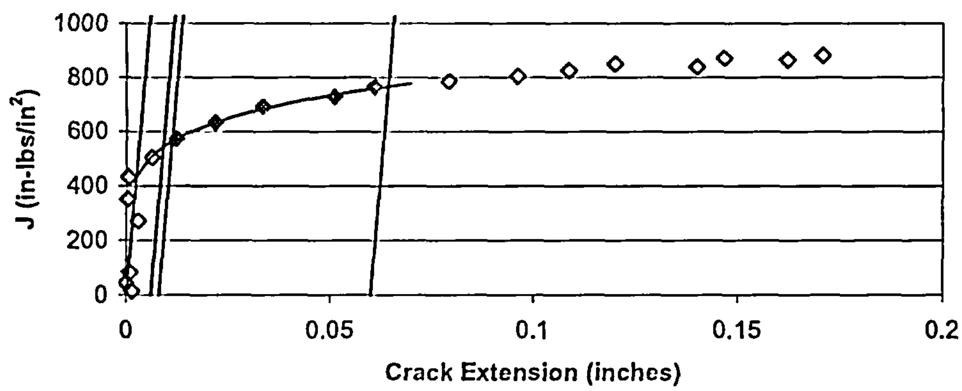
9.8.2.2 aoq data points fit >8

Points fit = 9 Valid

$R^2 > 0.96$

Regression = 0.80320824 Invalid

## Specimen WT13 $J_{IC}$ Analysis




| Unload Number | Δa (inches) | J (in-lbs/in$^2$) | Qualified |
|---|---|---|---|
| 1 | 0.001423 | 15.52 | |
| 2 | -1.9E-05 | 44.15 | |
| 3 | 0.000982 | 84.54 | |
| 4 | -0.001674 | 138.36 | |
| 5 | -0.00241 | 202.56 | |
| 6 | 0.002951 | 272.18 | |
| 7 | 0.000384 | 350.92 | |
| 8 | 0.000547 | 432.55 | |
| 9 | 0.00628 | 504.06 | * |
| 10 | 0.012262 | 572.21 | * |
| 11 | 0.021831 | 632.67 | * |
| 12 | 0.033538 | 691.48 | * |
| 13 | 0.051139 | 727.34 | * |
| 14 | 0.060957 | 763.85 | |
| 15 | 0.079267 | 785.25 | |
| 16 | 0.09613 | 802.53 | |
| 17 | 0.108666 | 825.22 | |
| 18 | 0.120047 | 850.41 | |
| 19 | 0.140086 | 838.12 | |
| 20 | 0.146793 | 869.44 | |
| 21 | 0.162094 | 864.32 | |
| 22 | 0.170738 | 881.08 | |

$J_{IC}$ Calc

| | | |
|---|---|---|
| C1 = | 702.44 | in-lbs/in$^2$ |
| C2 = | 0.1761 | |
| $J_Q$ = | 563 | in-lbs/in$^2$ |

Validity Requirements

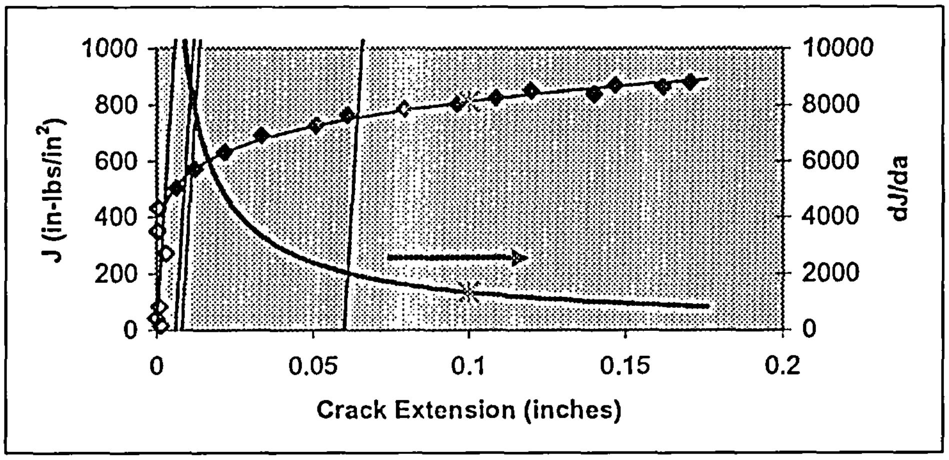
| | | |
|---|---|---|
| A9.6.4 | Data Grouping | Valid |
| A9.6.6.6.6 | Min. 5 Qualified | Valid |
| A9.8.1 | C2 <1 | Valid |
| A9.9.3 | Power Law Slope < $\Delta_Y$ | Valid |

Note: Test Does Not Meet Validity Requirements for Crack Extension

$J_Q$ = 563 in-lbs/in$^2$

$K_{JQ}$ = 130 ksi-in$^{1/2}$

## Specimen WT13
### Analysis of Toughness at 0.1 Inch Crack Extension




| Unload Number | Ha (inches) | J | Qualified |
|---|---|---|---|
| 1 | 0.001423 | 15.52 | |
| 2 | -1.9E-05 | 44.15 | |
| 3 | 0.000982 | 84.54 | |
| 4 | -0.001674 | 138.36 | |
| 5 | -0.00241 | 202.56 | |
| 6 | 0.002951 | 272.18 | |
| 7 | 0.000384 | 350.92 | |
| 8 | 0.000547 | 432.55 | |
| 9 | 0.00628 | 504.06 | * |
| 10 | 0.012262 | 572.21 | * |
| 11 | 0.021831 | 632.67 | * |
| 12 | 0.033538 | 691.48 | * |
| 13 | 0.051139 | 727.34 | * |
| 14 | 0.060957 | 763.85 | * |
| 15 | 0.079267 | 785.25 | * |
| 16 | 0.09613 | 802.53 | * |
| 17 | 0.108666 | 825.22 | * |
| 18 | 0.120047 | 850.41 | * |
| 19 | 0.140086 | 838.12 | * |
| 20 | 0.146793 | 869.44 | * |
| 21 | 0.162094 | 864.32 | * |
| 22 | 0.170738 | 881.08 | * |

<u>J at 0.1 inches</u>

| | | |
|---|---|---|
| C1 = | 696.01 | in-lbs/in$^2$ |
| C2 = | 0.1657 | |
| $J_{0.1}$ = | 812 | in-lbs/in$^2$ |
| $dJ/da_{0.1}$ = | 1346 | in-lbs/in$^2$/in |

## J-Integral Test Parameters

| | | |
|---|---|---|
| Operator's Name: | G.Evans | |
| Job Number: | WATTS BARS | |
| Specimen ID: | WT-14 | |
| Material: | PRESSURE | |
| Test Temperature: | 390 | F |
| Test Date: | 4/20/04 | |
| | | |
| Test Param File Name: | WATTS BAR WT-14 390 F-4 | |
| | | |
| Young's Modulus: | 27500000 | psi |
| Yield Stress: | 78000 | psi |
| Tensile Strength: | 99000 | psi |
| Poisson's Ratio: | 0.3 | |
| | | |
| Specimen Type | CT | |
| Width: | 1 | in |
| B gross: | 0.5 | in |
| B net: | 0.4 | in |
| Load Point Half Span: | 0.275 | in |
| COD HALF Span: | 0.0775 | in |
| | | |
| Ramp Rate for Load/Unload: | 0.000167 | in/sec |
| LPD Start Point for Load/Unload: | 0.003 | in |
| LPD Increment for Load/Unload : | 0.002 | in |
| Hold Duration at Peak: | 6 | sec |

## Specimen WT14 Crack Length Calculations

| Unload Number | Load (lbs) | Displacement (inches) | Unloading Compliance (inch/lb) | Radius of Rotation | Theta (degrees) | Corrected Compliance (in/lb) | Normalized Compliance ($B_eEC$) | u | Crack Length (inches) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 527 | 0.002939 | 4.1294E-06 | 0.79049086 | 0.106521 | 4.13287E-06 | 53.27527312 | 0.120497 | 0.569656 |
| 2 | 1063 | 0.005085 | 4.1496E-06 | 0.7848279 | 0.185643 | 4.15569E-06 | 53.56947712 | 0.120205 | 0.57065 |
| 3 | 1565 | 0.007098 | 4.1188E-06 | 0.78532491 | 0.258987 | 4.12728E-06 | 53.20321807 | 0.120568 | 0.569411 |
| 4 | 2051 | 0.009106 | 4.1735E-06 | 0.78470562 | 0.332537 | 4.18457E-06 | 53.94173606 | 0.119839 | 0.571897 |
| 5 | 2611 | 0.011187 | 4.2131E-06 | 0.78594866 | 0.407914 | 4.22683E-06 | 54.48650732 | 0.11931 | 0.573703 |
| 6 | 2707 | 0.011779 | 4.2062E-06 | 0.78685128 | 0.429015 | 4.22063E-06 | 54.40651137 | 0.119388 | 0.573439 |
| 7 | 3044 | 0.013775 | 4.2174E-06 | 0.78671949 | 0.501831 | 4.23435E-06 | 54.58345705 | 0.119217 | 0.574021 |
| 8 | 3252 | 0.015692 | 4.1662E-06 | 0.78701066 | 0.571493 | 4.18532E-06 | 53.9514344 | 0.11983 | 0.57193 |
| 9 | 3399 | 0.017104 | 4.167E-06 | 0.78596483 | 0.623776 | 4.18794E-06 | 53.98517314 | 0.119797 | 0.572042 |
| 10 | 3533 | 0.018985 | 4.1704E-06 | 0.78602107 | 0.69237 | 4.19368E-06 | 54.05913023 | 0.119725 | 0.572288 |
| 11 | 3601 | 0.020964 | 4.1747E-06 | 0.78614418 | 0.764475 | 4.20053E-06 | 54.14751801 | 0.119639 | 0.572582 |
| 12 | 3605 | 0.022952 | 4.1587E-06 | 0.78629102 | 0.83687 | 4.18695E-06 | 53.97239381 | 0.119809 | 0.572 |

## Specimen WT14
## Physical Crack Lengths

| | Precrack | | Precrack |
|---|---|---|---|
| Side 1 | 0.5169 | Side 1 | #N/A |
| 1/8 point | 0.5129 | 1/8 point | #N/A |
| 1/4 point | 0.5129 | 1/4 point | #N/A |
| 3/8 point | 0.521 | 3/8 point | #N/A |
| 1/2 point | 0.519 | 1/2 point | #N/A |
| 5/8 point | 0.521 | 5/8 point | #N/A |
| 3/4 point | 0.519 | 3/4 point | #N/A |
| 7/8 point | 0.519 | 7/8 point | #N/A |
| Side 2 | 0.519 | Side 2 | #N/A |
| length | 0.518 | length | #N/A |

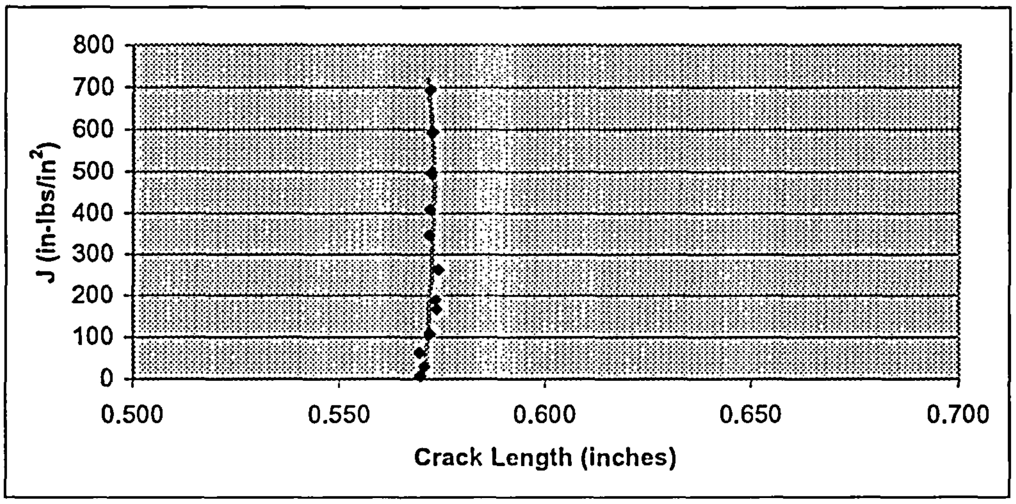
Validity Requirements

| | | | |
|---|---|---|---|
| 7.4.2 | Fatigue Precrack = | 0.080 > .050 | Valid |
| | Initial a/W = | 0.518 | Valid |
| 7.4.5 | Precracking Conducted Prior to Irradiation | | Valid |
| 9.1.4.1 | Original Crack Size | | |
| | Min. Variance = | 0.95% | Valid |
| | Max. Variance = | 0.61% | |
| 9.1.4.2 | Final Crack Size | | |
| | Min. Variance = | #N/A | Invalid |
| | Max. Variance = | #N/A | Invalid |
| 9.1.5.1 | Crack Extension | | |
| | Average = | #N/A inches | |
| | Min= | #N/A | Invalid |
| 9.1.5.2 | Crack Extension Prediction | | |
| | Measured = | #N/A | |
| | Predicted = | #N/A | |
| | Prediction Error = | #N/A | |
| | $0.2\ b_o$ = | 0.095665 | |
| | Crack Extension > $0.2\ b_o$ | | |
| | Prediction Error Should be less than: | | |
| | $0.03\ b_o$ = | 0.0111 | Invalid |

## Specimen WT14 Determination of J-Integral

| Unload Number | Load (lbs) | Displacement (inches) | Corrected Compliance (in/lb) | Crack Length (inches) | a/W | Plastic Displacement (inches) | Plastic Area (in-lbs) | f(a/W) | K (ksi-in$^{1/2}$) | Jelastic (in-lbs/in$^2$) | eta | gamma | Jplastic (in-lbs/in$^2$) | Jtotal (in-lbs/in$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 527 | 0.00294 | 4.1329E-06 | 0.5697 | 0.5697 | 0.00076 | 0.200567 | 12.180 | 14.82 | 7.27 | 2.22464 | 1.327062 | 0.00 | 7.27 |
| 2 | 1063 | 0.00509 | 4.1557E-06 | 0.5706 | 0.5706 | 0.00067 | 0.126609 | 12.224 | 30.00 | 29.79 | 2.224121 | 1.326306 | -1.02 | 28.77 |
| 3 | 1565 | 0.00710 | 4.1273E-06 | 0.5694 | 0.5694 | 0.00064 | 0.089456 | 12.170 | 43.98 | 63.99 | 2.224767 | 1.327247 | -1.54 | 62.46 |
| 4 | 2051 | 0.00911 | 4.1846E-06 | 0.5719 | 0.5719 | 0.00052 | -0.124385 | 12.280 | 58.18 | 111.99 | 2.22347 | 1.325358 | -4.47 | 107.53 |
| 5 | 2611 | 0.01119 | 4.2268E-06 | 0.5737 | 0.5737 | 0.00015 | -0.988037 | 12.361 | 74.53 | 183.81 | 2.222527 | 1.323986 | -16.38 | 167.43 |
| 6 | 2707 | 0.01178 | 4.2206E-06 | 0.5734 | 0.5734 | 0.00035 | -0.449617 | 12.349 | 77.20 | 197.22 | 2.222665 | 1.324186 | -8.91 | 188.31 |
| 7 | 3044 | 0.01378 | 4.2344E-06 | 0.5740 | 0.5740 | 0.00089 | 1.079083 | 12.375 | 87.00 | 250.45 | 2.222361 | 1.323744 | 12.34 | 262.79 |
| 8 | 3252 | 0.01569 | 4.1853E-06 | 0.5719 | 0.5719 | 0.00208 | 4.844561 | 12.281 | 92.23 | 281.50 | 2.223453 | 1.325333 | 64.88 | 346.38 |
| 9 | 3399 | 0.01710 | 4.1879E-06 | 0.5720 | 0.5720 | 0.00287 | 7.458214 | 12.286 | 96.45 | 307.86 | 2.223394 | 1.325248 | 101.06 | 408.92 |
| 10 | 3533 | 0.01899 | 4.1937E-06 | 0.5723 | 0.5723 | 0.00417 | 11.9697 | 12.297 | 100.33 | 333.12 | 2.223265 | 1.325061 | 163.47 | 496.59 |
| 11 | 3601 | 0.02096 | 4.2005E-06 | 0.5726 | 0.5726 | 0.00584 | 17.91749 | 12.310 | 102.39 | 346.89 | 2.223112 | 1.324838 | 245.75 | 592.64 |
| 12 | 3605 | 0.02295 | 4.1869E-06 | 0.5720 | 0.5720 | 0.00786 | 25.20362 | 12.284 | 102.27 | 346.09 | 2.223416 | 1.32528 | 347.30 | 693.39 |

## Specimen WT14 $a_{oq}$ Calculations




aoq = 0.5709

Measured Final= #N/A

| Unload Number | Load (lbs) | Displacement (inches) | Jtotal (in-lbs/in$^2$) | Crack Length (inches) | a-J/2ł$y$ (inches) | $J^2$ | $J^3$ |
|---|---|---|---|---|---|---|---|
| 1 | 527 | 0.00294 | 7.27 | 0.5697 | 0.5696 | 52.85 | 384 |
| 2 | 1063 | 0.00509 | 28.77 | 0.5706 | 0.5705 | 827.79 | 23817 |
| 3 | 1565 | 0.00710 | 62.46 | 0.5694 | 0.5691 | 3900.80 | 243630 |
| 4 | 2051 | 0.00911 | 107.53 | 0.5719 | 0.5713 | 11562.42 | 1243292 |
| 5 | 2611 | 0.01119 | 167.43 | 0.5737 | 0.5728 | 28032.40 | 4693431 |
| 6 | 2707 | 0.01178 | 188.31 | 0.5734 | 0.5724 | 35459.31 | 6677216 |
| 7 | 3044 | 0.01378 | 262.79 | 0.5740 | 0.5725 | 69057.47 | 18147467 |
| 8 | 3252 | 0.01569 | 346.38 | 0.5719 | 0.5700 | 119982.19 | 41559966 |
| 9 | 3399 | 0.01710 | 408.92 | 0.5720 | 0.5697 | 167217.25 | 68378824 |
| 10 | 3533 | 0.01899 | 496.59 | 0.5723 | 0.5695 | 246603.14 | 122461027 |
| 11 | 3601 | 0.02096 | 592.64 | 0.5726 | 0.5692 | 351219.97 | 208146353 |
| 12 | 3605 | 0.02295 | 693.39 | 0.5720 | 0.5681 | 480794.22 | 333379471 |
| 13 | | | | | | | |
| 14 | | | | | | | |
| 15 | | | | | | | |
| 16 | | | | | | | |
| 17 | | | | | | | |
| 18 | | | | | | | |
| 19 | | | | | | | |
| 20 | | | | | | | |
| 21 | | | | | | | |
| 22 | | | | | | | |

Validity Requirements

9.8.2.1 Error in aoq prediction less than 0.01W

aoq = 0.5709

Measured = 0.5178 Invalid

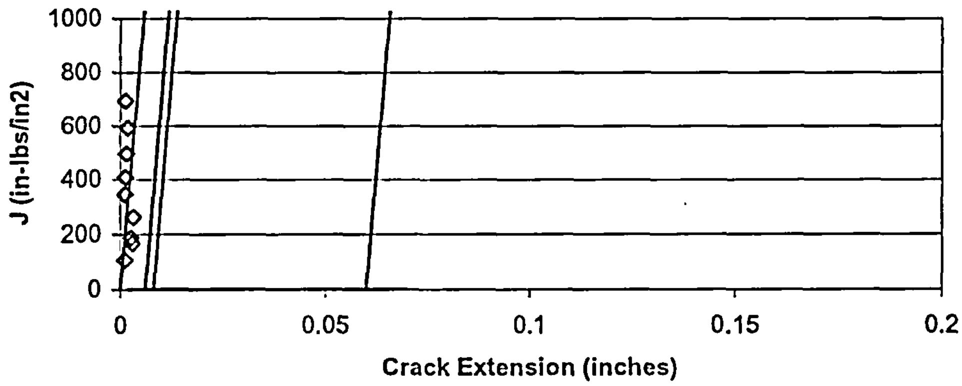
9.8.2.2 aoq data points fit >8

Points fit = 12 Valid

$R^2 > 0.96$

Regression = 0.40787639 Invalid

## Specimen WT14 $J_{IC}$ Analysis




| Unload Number | Ha (inches) | J (in-lbs/in$^2$) | Qualified |
|---|---|---|---|
| 1 | -0.001208 | 7.27 | |
| 2 | -0.000214 | 28.77 | |
| 3 | -0.001452 | 62.46 | |
| 4 | 0.001034 | 107.53 | |
| 5 | 0.002839 | 167.43 | |
| 6 | 0.002576 | 188.31 | |
| 7 | 0.003158 | 262.79 | |
| 8 | 0.001066 | 346.38 | |
| 9 | 0.001179 | 408.92 | * |
| 10 | 0.001425 | 496.59 | * |
| 11 | 0.001719 | 592.64 | * |
| 12 | 0.001136 | 693.39 | * |
| 13 | | | * |
| 14 | | | |
| 15 | | | |
| 16 | | | |
| 17 | | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 21 | | | |
| 22 | | | |

$J_{IC}$ Calc

| | | |
|---|---|---|
| C1 = | #NUM! | in-lbs/in$^2$ |
| C2 = | #NUM! | |
| $J_Q$ = | #N/A | in-lbs/in$^2$ |

Validity Requirements

| | | |
|---|---|---|
| A9.6.4 | Data Grouping | NA() |
| A9.6.6.6.6 | Min. 5 Qualified | NA() |
| A9.8.1 | C2 <1 | NA() |
| A9.9.3 | Power Law Slope < $H_Y$ | NA() |

Note: Test Does Not Meet Validity Requirements for Crack Extension

$J_Q$ = #N/A in-lbs/in$^2$

$K_{JQ}$ = #N/A ksi-in$^{1/2}$

## J-Integral Test Parameters

| | | |
|---|---|---|
| Operator's Name: | G.Evans | |
| Job Number: | WATTS BARS | |
| Specimen ID: | WT-15 | |
| Material: | PRESSURE | |
| Test Temperature: | 390 | F |
| Test Date: | 6/11/04 | |
| Test Param File Name: | WATTS BAR WT-15 390 F-2 | |
| Young's Modulus: | 27500000 | psi |
| Yield Stress: | 78000 | psi |
| Tensile Strength: | 99000 | psi |
| Poisson's Ratio: | 0.3 | |
| Specimen Type | CT | |
| Width: | 1 | in |
| B gross: | 0.5 | in |
| B net: | 0.4 | in |
| Load Point Half Span: | 0.275 | in |
| COD HALF Span: | 0.078 | in |
| amp Rate for Load/Unload: | 0.000167 | in/sec |
| Start Point for Load/Unload: | 0.003 | in |
| ncrement for Load/Unload : | 0.002 | in |
| Hold Duration at Peak: | 6 | sec |

## Specimen WT15 Crack Length Calculations

| Unload Number | Load (lbs) | Displacement (inches) | Unloading Compliance (inch/lb) | Radius of Rotation | Theta (degrees) | Corrected Compliance (in/lb) | Normalized Compliance ($B_eEC$) | u | Crack Length (inches) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1009 | 0.002956 | 2.7471E-06 | 0.75737022 | 0.111823 | 2.7496E-06 | 35.44405614 | 0.143813 | 0.491549 |
| 2 | 1593 | 0.004937 | 2.9101E-06 | 0.74577456 | 0.189681 | 2.9147E-06 | 37.57236649 | 0.14026 | 0.503237 |
| 3 | 2157 | 0.006944 | 2.927E-06 | 0.75161833 | 0.264735 | 2.93339E-06 | 37.81326282 | 0.139875 | 0.504508 |
| 4 | 2655 | 0.008956 | 2.9188E-06 | 0.75225409 | 0.341176 | 2.9271E-06 | 37.73214136 | 0.140004 | 0.504081 |
| 5 | 3006 | 0.010881 | 2.9582E-06 | 0.75204056 | 0.414655 | 2.96841E-06 | 38.26469829 | 0.139162 | 0.506864 |
| 6 | 3287 | 0.012866 | 2.9572E-06 | 0.75343214 | 0.489429 | 2.96928E-06 | 38.27583891 | 0.139145 | 0.506922 |
| 7 | 3477 | 0.014858 | 2.9548E-06 | 0.753461 | 0.565225 | 2.96877E-06 | 38.26926432 | 0.139155 | 0.506888 |
| 8 | 3618 | 0.016772 | 3.0013E-06 | 0.75344397 | 0.638096 | 3.01736E-06 | 38.89561609 | 0.138186 | 0.5101 |
| 9 | 3691 | 0.018862 | 3.0242E-06 | 0.75505003 | 0.716138 | 3.0424E-06 | 39.21848855 | 0.137694 | 0.511731 |
| 10 | 3655 | 0.020835 | 3.1688E-06 | 0.75586543 | 0.79025 | 3.18988E-06 | 41.1195768 | 0.134908 | 0.521005 |
| 11 | 3616 | 0.022819 | 3.2326E-06 | 0.76050229 | 0.860279 | 3.25599E-06 | 41.97173484 | 0.133716 | 0.524988 |

# Specimen WT15
# Physical Crack Lengths

| | Precrack | | Precrack |
|---|---|---|---|
| Side 1 | 0.5081 | Side 1 | #N/A |
| 1/8 point | 0.5171 | 1/8 point | #N/A |
| 1/4 point | 0.5135 | 1/4 point | #N/A |
| 3/8 point | 0.5171 | 3/8 point | #N/A |
| 1/2 point | 0.5135 | 1/2 point | #N/A |
| 5/8 point | 0.5135 | 5/8 point | #N/A |
| 3/4 point | 0.5099 | 3/4 point | #N/A |
| 7/8 point | 0.5117 | 7/8 point | #N/A |
| Side 2 | 0.4992 | Side 2 | #N/A |
| length | 0.512 | length | #N/A |

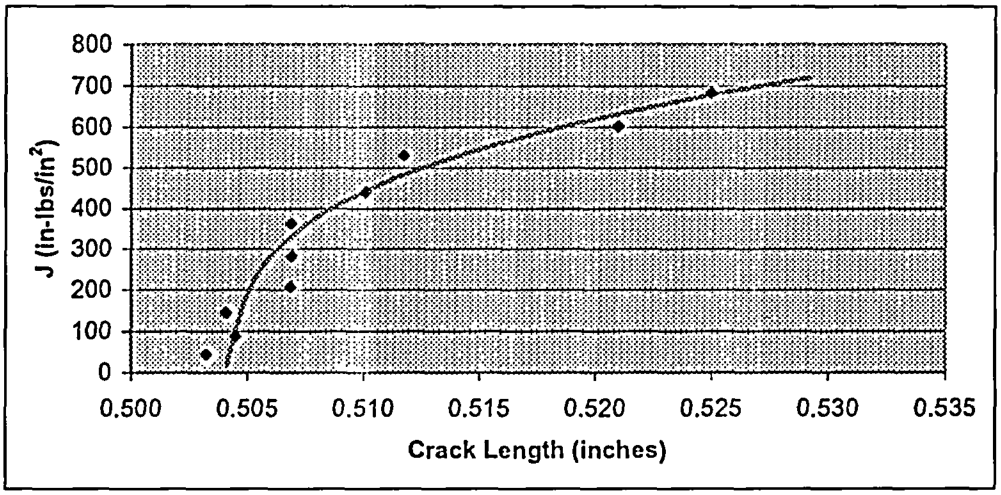
Validity Requirements

| | | | |
|---|---|---|---|
| 7.4.2 | Fatigue Precrack = | 0.074 > .050 | Valid |
| | Initial a/W = | 0.512 | Valid |
| 7.4.5 | Precracking Conducted Prior to Irradiation | | Valid |
| 9.1.4.1 | Original Crack Size | | |
| | Min. Variance = | 2.59% | Valid |
| | Max. Variance = | 0.90% | |
| 9.1.4.2 | Final Crack Size | | |
| | Min. Variance = | #N/A | #N/A |
| | Max. Variance = | #N/A | #N/A |
| 9.1.5.1 | Crack Extension | | |
| | Average = | #N/A inches | |
| | Min= | #N/A | #N/A |
| 9.1.5.2 | Crack Extension Prediction | | |
| | Measured = | #N/A | |
| | Predicted = | 0.170738 | |
| | Prediction Error = | #N/A | |
| | $0.2\ b_O$ = | 0.095665 | |
| | Crack Extension > $0.2\ b_O$ | | |
| | Prediction Error Should be less than: | | |
| | $0.03\ b_O$ = | 0.0111 | #N/A |

## Specimen WT15 Determination of J-Integral

| Unload Number | Load (lbs) | Displacement (inches) | Corrected Compliance (in/lb) | Crack Length (inches) | a/W | Plastic Displacement (inches) | Plastic Area (in-lbs) | f(a/W) | K (ksi-in$^{1/2}$) | Jelastic (in-lbs/in$^2$) | eta | gamma | Jplastic (in-lbs/in$^2$) | Jtotal (in-lbs/in$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1009 | 0.00296 | 2.7496E-06 | 0.4915 | 0.4915 | 0.00018 | 0.092237 | 9.413 | 21.92 | 15.91 | 2.265411 | 1.386423 | 0.00 | 15.91 |
| 2 | 1593 | 0.00494 | 2.9147E-06 | 0.5032 | 0.5032 | 0.00029 | 0.236511 | 9.756 | 35.89 | 42.63 | 2.25931 | 1.37754 | 1.70 | 44.33 |
| 3 | 2157 | 0.00694 | 2.9334E-06 | 0.5045 | 0.5045 | 0.00062 | 0.842972 | 9.795 | 48.79 | 78.76 | 2.258647 | 1.376574 | 9.04 | 87.80 |
| 4 | 2655 | 0.00896 | 2.9271E-06 | 0.5041 | 0.5041 | 0.00119 | 2.209017 | 9.782 | 59.97 | 119.02 | 2.25887 | 1.376898 | 25.66 | 144.68 |
| 5 | 3006 | 0.01088 | 2.9684E-06 | 0.5069 | 0.5069 | 0.00196 | 4.40043 | 9.867 | 68.48 | 155.20 | 2.257417 | 1.374783 | 52.02 | 207.22 |
| 6 | 3287 | 0.01287 | 2.9693E-06 | 0.5069 | 0.5069 | 0.00311 | 8.008444 | 9.869 | 74.91 | 185.69 | 2.257387 | 1.374739 | 96.05 | 281.75 |
| 7 | 3477 | 0.01486 | 2.9688E-06 | 0.5069 | 0.5069 | 0.00454 | 12.84468 | 9.868 | 79.23 | 207.72 | 2.257404 | 1.374765 | 155.11 | 362.83 |
| 8 | 3618 | 0.01677 | 3.0174E-06 | 0.5101 | 0.5101 | 0.00586 | 17.52359 | 9.967 | 83.28 | 229.51 | 2.255728 | 1.372324 | 210.68 | 440.19 |
| 9 | 3691 | 0.01886 | 3.0424E-06 | 0.5117 | 0.5117 | 0.00763 | 24.01482 | 10.019 | 85.41 | 241.38 | 2.254876 | 1.371085 | 289.32 | 530.70 |
| 10 | 3655 | 0.02084 | 3.1899E-06 | 0.5210 | 0.5210 | 0.00917 | 29.68398 | 10.319 | 87.11 | 251.11 | 2.250036 | 1.364037 | 350.92 | 602.03 |
| 11 | 3616 | 0.02282 | 3.2560E-06 | 0.5250 | 0.5250 | 0.01105 | 36.48578 | 10.453 | 87.29 | 252.13 | 2.247956 | 1.361009 | 431.84 | 683.97 |

**Specimen WT15 $a_{oq}$ Calculations**




aoq = 0.5040

Measured
Final= #N/A

| Unload Number | Load (lbs) | Displacement (inches) | Jtotal (in-lbs/in²) | Crack Length (inches) | a-J/2Jy (inches) | $J^2$ | $J^3$ |
|---|---|---|---|---|---|---|---|
| 1 | 1009 | 0.00296 | 15.91 | 0.4915 | 0.4915 | 253.01 | 4024 |
| 2 | 1593 | 0.00494 | 44.33 | 0.5032 | 0.5030 | 1964.79 | 87091 |
| 3 | 2157 | 0.00694 | 87.80 | 0.5045 | 0.5040 | 7708.63 | 676808 |
| 4 | 2655 | 0.00896 | 144.68 | 0.5041 | 0.5033 | 20931.13 | 3028231 |
| 5 | 3006 | 0.01088 | 207.22 | 0.5069 | 0.5057 | 42941.35 | 8898432 |
| 6 | 3287 | 0.01287 | 281.75 | 0.5069 | 0.5053 | 79382.36 | 22365880 |
| 7 | 3477 | 0.01486 | 362.83 | 0.5069 | 0.5048 | 131644.60 | 47764430 |
| 8 | 3618 | 0.01677 | 440.19 | 0.5101 | 0.5076 | 193770.90 | 85296822 |
| 9 | 3691 | 0.01886 | 530.70 | 0.5117 | 0.5087 | 281643.73 | 149468659 |
| 10 | 3655 | 0.02084 | 602.03 | 0.5210 | 0.5176 | 362437.46 | 218197425 |
| 11 | 3616 | 0.02282 | 683.97 | 0.5250 | 0.5211 | 467809.04 | 319965321 |

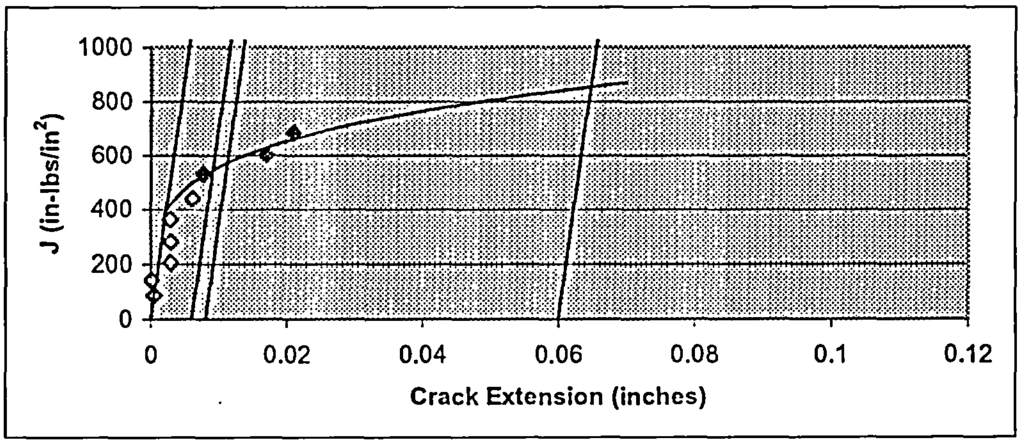
Validity Requirements

9.8.2.1 Error in aoq prediction less than 0.01W
aoq = 0.5040
Measured = 0.5125 Valid

9.8.2.2 aoq data points fit >8
Points fit = 10 Valid

$R^2 > 0.96$
Regression = 0.95102334 Invalid

## Specimen WT15 $J_{IC}$ Analysis




| Unload Number | $\Delta$a (inches) | J (in-lbs/in$^2$) | Qualified |
|---|---|---|---|
| 1 | -0.012455 | 15.91 | |
| 2 | -0.000768 | 44.33 | |
| 3 | 0.000504 | 87.80 | |
| 4 | 7.66E-05 | 144.68 | |
| 5 | 0.00286 | 207.22 | |
| 6 | 0.002917 | 281.75 | |
| 7 | 0.002883 | 362.83 | |
| 8 | 0.006096 | 440.19 | |
| 9 | 0.007726 | 530.70 | * |
| 10 | 0.017 | 602.03 | * |
| 11 | 0.020984 | 683.97 | * |
| 12 | | | |
| 13 | | | |
| 14 | | | |
| 15 | | | |
| 16 | | | |
| 17 | | | |
| 18 | | | |
| 19 | | | |
| 20 | | | |
| 21 | | | |
| 22 | | | |

$J_{IC}$ Calc

| | |
|---|---|
| C1 = | 762.47 in-lbs/in$^2$ |
| C2 = | 0.2282 |
| $J_Q$ = | 573 in-lbs/in$^2$ |

Validity Requirements

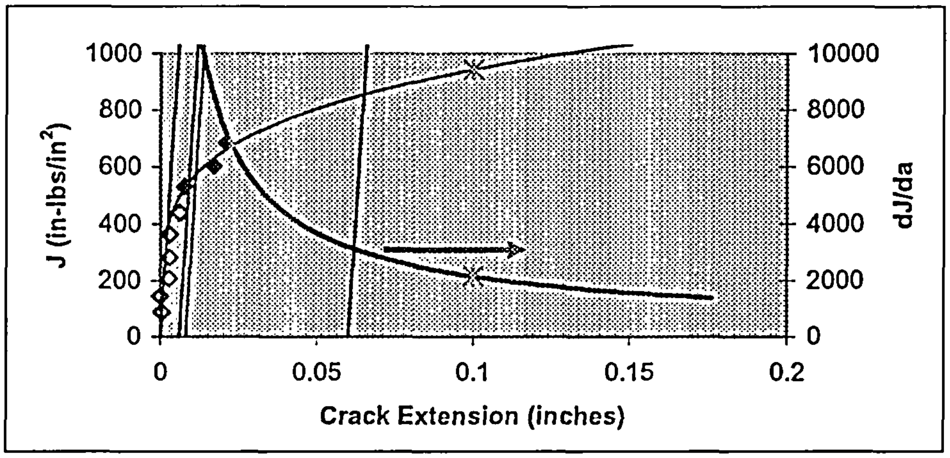
| | | |
|---|---|---|
| A9.6.4 | Data Grouping | Invalid |
| A9.6.6.6.6 | Min. 5 Qualified | Invalid |
| A9.8.1 | C2 <1 | Valid |
| A9.9.3 | Power Law Slope < $J_Y$ | Valid |

Note: Test Does Not Meet Validity Requirements for Crack Extension

$J_Q$ = 573 in-lbs/in$^2$

$K_{JQ}$ = 132 ksi-in$^{1/2}$

## Specimen WT15
### Analysis of Toughness at 0.1 Inch Crack Extension




| Unload Number | Ja (inches) | J | Qualified |
|---|---|---|---|
| 1 | -0.012455 | 15.91 | |
| 2 | -0.000768 | 44.33 | |
| 3 | 0.000504 | 87.80 | |
| 4 | 7.66E-05 | 144.68 | |
| 5 | 0.00286 | 207.22 | |
| 6 | 0.002917 | 281.75 | |
| 7 | 0.002883 | 362.83 | |
| 8 | 0.006096 | 440.19 | |
| 9 | 0.007726 | 530.70 | * |
| 10 | 0.017 | 602.03 | * |
| 11 | 0.020984 | 683.97 | * |

<u>J at 0.1 inches</u>

| | | |
|---|---|---|
| C1 = | 762.47 | in-lbs/in$^2$ |
| C2 = | 0.2282 | |
| $J_{0.1}$ = | 943 | in-lbs/in$^2$ |
| $dJ/da_{0.1}$ = | 2152 | in-lbs/in$^2$/in |